Pitch and Timing in the Songs of Deaf Children With Cochlear Implants

Takayuki Nakata
Nagasaki Junshin Catholic University, Japan

Sandra E. Trehub
University of Toronto, Ontario

Chisato Mitani
National Hospital Organization
Nagasaki Medical Center, Japan

Yukihiko Kanda
Nagasaki Bell Hearing Center, Japan

congenitally deaf children (5–10 years) who use cochlear implants and hearing children of comparable age sang songs from memory. Analyses of their performances revealed timing similarities in the songs of deaf and hearing children but substantial differences in pitch patterning. Whereas hearing children accurately reproduced the relative pitch patterns of the songs they sang, deaf children did not. Deaf children's pitch range was considerably smaller than that of hearing children, and their pitch changes were unrelated to the direction of pitch change in the target songs. For child implant users, the power and pleasure of music may arise primarily from its rhythm.

Received February 2, 2006, accepted July 22, 2006

Key words: singing, children, deaf, pitch, timing, cochlear implant

Cochlear implants are becoming the prostheses of choice for many deaf children and adults. In general, the devices, which convert acoustic input into electrical signals that are transmitted to the brain (Loizou, 1999), enable deaf adults to perceive speech effectively in favorable (i.e., quiet) listening environments. These implants also enable many congenitally deaf children to acquire the spoken language of their community (Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, 2000). Because the devices provide limited spectral detail, users experience difficulty in situations that require good spectral resolution, for example, perceiving speech in noise (Qin & Oxenham, 2003), recognizing voices (Cleary, Pisoni, & Kirk, 2005), and perceiving pitch patterns (Gfeller et al., 2005; Kong, Cruz, Jones, & Zeng, 2004). As a result, adults who lose their hearing are unable to recognize familiar music in the post-implant period from pitch relations alone (Fujita & Ito, 1999; Gfeller et al., 2000). It is not surprising, then, that their interest in music tends to wane or disappear altogether (Gfeller et al., 2000; McDermott & McKay, 1997).

Like adults, congenitally deaf children are unable to identify frequently heard melodies on the basis of pitch cues alone (Stordahl, 2002; Vongpaisal, Trehub, & Schellenberg, 2006), but they can identify familiar pop songs from the original recordings or from the original instrumental portions (Vongpaisal et al., 2006). Such children can also identify the musical soundtracks from their favorite television programs (Mitani et al., in press; Nakata et al., 2005). Child implant users' success in the context of multiple acoustic cues from the original recordings, along with their failure in the limited context of the main melody, implies that their representation of music differs substantially from that of hearing listeners.

Hearing adults' robust representation of abstract, relational features of familiar music (Dowling, 1999) enables them to sing familiar songs and art-music themes (e.g., the opening bars of Beethoven's Fifth Symphony) from memory. Their representation of absolute features of music may be less robust, but their renditions of well-known pop songs are within two semitones of the pitch level of canonical performances (Levitin, 1994) and within 8% of the original tempo (Levitin & Cook, 1996). Moreover, adults distinguish excerpts of familiar TV soundtracks from foils that are pitch-shifted by one or two semitones (Schellenberg & Trehub, 2003), which confirms their long-term memory for pitch level. Even infants exhibit long-term memory for the pitch level of expressive musical performances (Volkova, Trehub, & Schellenberg, 2006).

Music Perception volume 24, issue 2, pp. 147–154, issn 0730-7829, electronic issn 1533-8312 DOI: mp.2006.24.2.147

Remarkably, adults also extract meaningful information from minuscule excerpts of music. For example, they identify familiar popular songs from a closed set (i.e., five song titles with artists) at better than chance levels after hearing 100–200 ms excerpts that provide timbral cues but no melodic or tempo cues (Schellenberg, Iverson, & McKinnon, 1999). Moreover, they report distinctive emotional responses to musical excerpts as brief as 250 ms (Bigand, Filipic, & Lalitte, 2005). Presumably, adults and children with normal hearing rely primarily on relative pitch and timing skills when they identify or produce music. Nevertheless, their representation of absolute features comes into play when they evaluate the quality or authenticity of specific musical renditions.

Unlike their adult counterparts with cochlear implants, congenitally deaf children with implants seem to derive considerable pleasure from music. They rate familiar music favorably, and they participate in a variety of musical activities including singing, dancing, and instrument training (Gfeller, Witt, Spencer, Stordahl, & Tomblin, 1998; Nakata et al., 2005; Vongpaisal et al., 2006). In principle, their positive ratings of music could stem from social desirability (Heyman & Legare, 2005) or peer influence, and their involvement in music could be attributed to parental pressure. However, neither factor can account for child implant users' high incidence of spontaneous singing (Nakata et al., 2005). Because children who use cochlear prostheses cannot recognize familiar music from its pitch patterning, rhythm may play a much greater role in music appreciation than it does for children with normal hearing. Indeed, the temporal features of music enable individuals to synchronize their behavior with others, which is presumed to have important social-emotional consequences (Benzon, 2001).

The present study is the first to examine the nature of singing in a sample of congenitally deaf children who use cochlear implants. Our principal goal was to determine the extent to which young, congenitally deaf implant users capture the relative pitch and timing of the original songs. To enable us to differentiate between characteristic limitations in children's singing and limitations arising specifically from cochlear implant use, we included a small sample of hearing children in the same age range. On the basis of adult implant users' good rhythm discrimination (Gfeller, Woodworth, Robin, Witt, & Knutson, 1997) and poor pitch discrimination (Fujita & Ito, 1999; Vandali et al., 2006) and child implant users' poor perception of pitch relations (Nakata et al., 2005; Vongpaisal et al., 2006), we expected the songs of child implant users to have reasonable temporal patterning but poor pitch patterning.

Method

Participants

The participants were 12 congenitally deaf Japanese children (4 boys, 8 girls) who were 5 to 10 years of age and 6 normally hearing Japanese children (1 boy, 5 girls) who were 5 to 9 years of age. Two additional deaf participants were excluded from consideration because the songs they sang were unknown to the experimenters, precluding evaluations of pitch or timing accuracy. All deaf children had unilateral cochlear implants, which they had used consistently for a minimum of 10 months ($M = 3$ years, 4 months). Before implantation, the deaf children had used bilateral hearing aids. Background information about the deaf and hearing children is shown in Table 1. The deaf children were relatively successful implant users by virtue of their placement in age-appropriate classes in regular schools and their ability to converse orally with hearing adults and children. Nine of the children with implants also used hearing aids in their contralateral ear despite limited residual hearing in that ear. At the time of testing, three children with implants and five of the six hearing children were taking music lessons outside of school.

Apparatus and Procedure

All children were tested individually. The deaf children were tested in a sound-attenuating booth during a routine follow-up visit at a hearing clinic. One hearing child (sibling of a child with implants) was tested at the hearing clinic, and the other hearing children were tested in a quiet room at their music school. To stimulate children's interest in singing, the experimenter first showed them a booklet of drawings based on popular children's songs. Then they were asked to sing songs that they knew well, a request with which all children readily complied. Their sung performances were recorded by means of a digital audio recorder (SONY TCD-D8) and microphone (EV Cobalt Co9).

Results

Table 2 indicates the songs sung and the number of notes analyzed. For children who sang more than one song, the song selected for acoustic analysis was the one most readily identified by the experimenter. As can be seen in Table 2, there was considerable variety in children's songs, which posed challenges of measurement and comparison. For deaf as well as hearing children, the songs were sung with

TABLE 1. Participant information

Child	Age of implant	Age at test	Hearing aid	Device	Coding
CI-1	6 years, 3 months	10 years, 4 months	yes	Cochlear SPrint	ACE
CI-2	6 years, 5 months	8 years, 5 months	yes	Cochlear SPrint	ACE
CI-3	2 years, 5 months	7 years, 1 month	yes	Advanced Bionics	SAS
CI-4	3 years, 8 months	5 years, 8 months	yes	Cochlear SPrint	ACE
CI-5	1 year, 11 months	7 years, 10 months	no	Cochlear Spectra 12	SPEAK
CI-6	2 years, 5 months	6 years, 9 months	yes	Cochlear SPrint	ACE
CI-7	4 years, 6 months	10 years, 2 months	no	Cochlear SPrint	SPEAK
CI-8	7 years	9 years, 3 months	yes	Cochlear SPrint	ACE
CI-9	6 years, 2months	7 years, 6 months	yes	Cochlear SPrint	ACE
CI-10	2 years, 5 months	5 years, 3 months	no	Cochlear SPrint	ACE
CI-11	3 years, 8 months	8 years, 2 months	yes	Cochlear SPrint	ACE
CI-12	4 years, 1 month	4 years, 11 months	yes	MED-EL	CIS
NH-1		6 years, 8 months			
NH-2		7 years, 10 months			
NH-3		8 years, 1 month			
NH-4		7 years			
NH-5		9 years, 11 months			
NH-6		9 years, 7 months			

words, but the words were excluded from consideration in the present study. Hearing children sang all the words correctly, but some deaf children omitted a few words along with the corresponding notes, either pausing momentarily or skipping those words and notes without pausing. Only one deaf child had a "deaf" voice quality and articulated the lyrics poorly. Pleasant affect was evident in most performances by hearing and deaf children, but this aspect was beyond the scope of the present investigation. Samples of singing by child implant users are available online (http://www.utm.utoronto.ca/~w3trehub/is/research.htm).

TABLE 2. Songs produced

Child	Song	Genre	Notes analyzed
CI-1	*Kimigayo*	Japanese anthem	32
CI-2	*Ano aoi sora-no youni*	Children's song	27
CI-3	*Ookina kuri*	Children's song	14
CI-4	*Tulip*	Children's song	36
CI-5	*Kaeru-no uta*	Children's song	23
CI-6	*Ooki-na kuri*	Children's song	38
CI-7	*Tulip*	Children's song	33
CI-8	*Kaeru-no uta*	Children's song	25
CI-9	*Ooki-na kuri*	Children's song	38
CI-10	*Zou-san*	Children's song	18
CI-11	*Kakko*	Children's song	25
CI-12	*Kakko*	Children's song	25
NH-1	*Anpanman*	TV theme song	41
NH-2	*Doraemon*	TV theme song	33
NH-3	*Gyuutan*	TV theme song	31
NH-4	*Ojii-san*	Children's song	42
NH-5	*Sanpo*	Children's song	34
NH-6	*Bokujo-no uta*	Children's song	56

Measures of pitch and timing were obtained for each sung note by means of Praat 4.3.18 speech analysis and synthesis software (Boersma & Weenink, 2005) on an iBook computer. Average fundamental frequency (F0 in Hz) was calculated for a stable portion of the vowel corresponding to each note. On the basis of a sound spectrogram of each child's singing, the onset of a note was identified as the beginning of the first vowel. Onset-to-onset times were computed from the onset of each note to the onset of the subsequent note. There were isolated cases of omitted notes, as when a child temporarily interrupted a performance or omitted words. These segments were excluded from consideration. Instead, pitch and timing calculations were limited to portions of the song that were sung continuously with the correct words. We established target onset-to-onset durations by determining relative durations for each song from a typical notated version of that song, then adjusting those durations in accordance with the child's tempo of singing. Target pitches for each song were established on the basis of the child's initial pitch for that song.

Figure 1 depicts observed and expected (target) aspects of pitch and timing from the first 15 beats of performances by a subsample of children with cochlear implants and those with normal hearing. Comparable figures depicting all children's performances are available online at http://www.utm.utoronto.ca/~w3trehub/is/research.htm. Deviations from target durations were computed by averaging the absolute percentage deviation

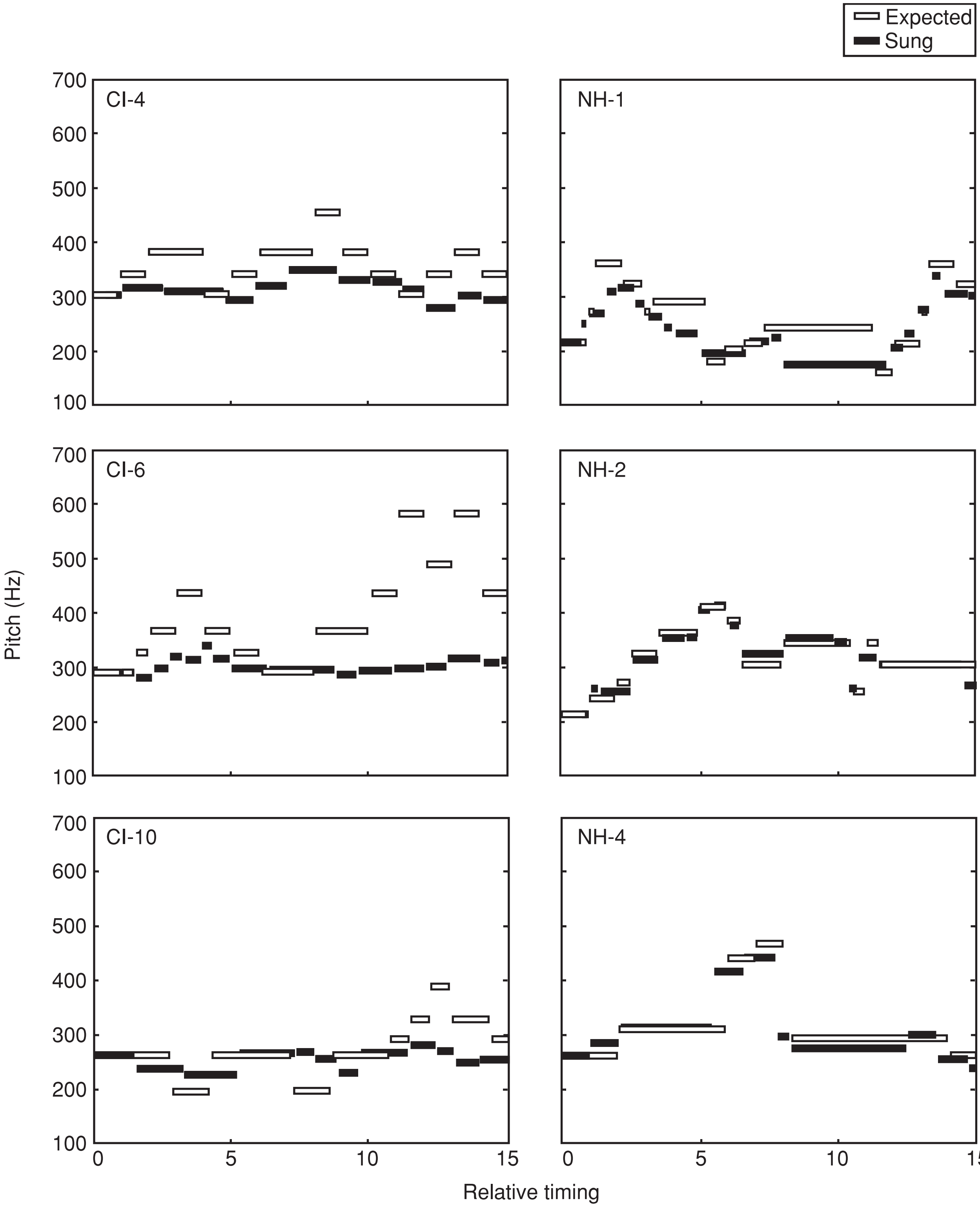

FIG. 1. Pitch and timing of the first 15 beats of familiar songs sung by a subsample of deaf children with cochlear implants (CI) and hearing children (NH). Open symbols show expected pitch and onset-to-onset times according to notated versions of the songs. Filled symbols show pitch and onset-to-onset times of children's actual performances.

from the target duration for each sung note. A pairwise *t* test revealed that deviations from target durations did not differ between children with implants ($M = 32.26$, $SD = 24.90$) and hearing children ($M = 21.00$, $SD = 10.47$), $t(16) = 1.05$, ns. Although timing deviations were larger than one would expect from older children and adults, the temporal patterning of the original songs was recognizable for all hearing children and for all but one child with implants.

The pitch range of implanted children's songs ($M = 76.58$ Hz, $SD = 31.15$) was substantially smaller than that of hearing children ($M = 238.83$ Hz, $SD = 40.07$), $t(16) = -9.49$, $p < .001$. In fact, the pitch range of hearing children's performances, which matched the expected pitch range, was over three (3.12) times as large as that of implanted children. To determine whether the pitch contours of deaf children's songs were simply compressed or entirely unrelated to the target pitch contours, the direction of pitch change (i.e., up or down) was examined for adjacent notes that involved pitch changes (i.e., repeated notes excluded). Not surprisingly, hearing children matched the direction of target pitch changes with near-perfect accuracy ($M = .96$, $SD = .05$), $t(5) = 21.97$, $p < .001$. By contrast, reproduction of directional changes in pitch by children with implants was at chance levels ($M = .48$, $SD = .19$), $t(11) = -.26$, and the difference between children with implants and hearing children was highly significant, $t(16) = -5.94$, $p < .001$. These difficulties with contour reproduction were not restricted to the very small pitch steps that are so common in music. In fact, the accuracy with which children with implants matched the target direction of pitch change did not differ for changes of three or more semitones ($M = 50.42\%$, $SD = 30.37$) or for those of one or two semitones ($M = 47.67\%$, $SD = 22.29$), $t(11) = -.26$, ns.

Pitch distances between adjacent sung notes were converted to cents (i.e., hundredths of a semitone). The mean deviation from the target pitch was computed by averaging the absolute value of the difference between the observed pitch change and the expected pitch change for all adjacent notes that were sung continuously. Deviations from target pitches were substantially greater for children with cochlear implants ($M = 243.25$ cents, $SD = 55.23$) than for hearing children ($M = 86.67$ cents, $SD = 45.21$), $t(16) = 5.99$, $p < .001$. When the original song had repeated pitches (i.e., target pitch change of zero), however, implanted children's absolute pitch shift ($M = 63.83$ cents, $SD = 35.12$) was significantly smaller than their absolute pitch shift for target pitches that shifted upward or downward ($M = 97.00$ cents, $SD = 42.69$), $t(11) = -2.36$, $p < .05$, indicating some differentiation of pitch repetitions from pitch changes.

Discussion

In the present study deaf children with cochlear implants reproduced the temporal patterning but not the pitch patterning of familiar songs. These findings are important for several reasons. For one thing, they confirm child implant users' long-term memory for music, as indicated by their recall of several features of the songs, most notably their temporal form. Previous research has indicated that deaf children with implants can identify familiar recordings of popular songs from the original, vocal-plus-instrumental renditions or from the original instrumental portions (Vongpaisal et al., 2006). They can also identify the sound tracks of familiar television programs (Mitani et al., in press; Nakata et al., 2005). The tasks in those studies were considerably less demanding than the present task, which required free recall rather than recognition from a closed set of alternatives. Thus, the present findings attest to child implant users' relatively robust memory for songs.

Congenitally deaf children's ability to sing songs also lends credence to the claim that they derive pleasure from music (Gfeller et al., 1998; Nakata et al., 2005; Vongpaisal et al., 2006). Without frequent singing of the target songs at home or elsewhere, child implant users would have been unable to remember the details that they reproduced. For the most part, their performances exuded the energy and vitality that are characteristic of hearing children's singing. Thus, congenitally deaf implant users' experience of music seems to be very different from that of implant users who lose their hearing as adults (Gfeller et al., 2000). Adult implant users must contend with the permanent loss of music as they remember it, which would interfere with their ability to enjoy the degraded musical input available to them. For congenitally deaf children, however, there is no comparable sense of loss to diminish the favorable aspects of music that are accessible.

Child implant users' ability to reproduce the temporal patterning but not the pitch patterning of songs mirrors the technical limitations of current implants and signal processing strategies (Wilson et al., 2005). Because the devices were designed for speech perception, they transform the auditory input in ways that optimize temporal envelope cues at the expense of spectral details (Loizou, 1999). These processing algorithms are adequate for speech reception (Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995; Wilson et al., 2005), but they are inadequate for music (Kong et al., 2004; Leal et al., 2003). Interestingly, child implant users' musical limitations have parallels with those of musically disabled (amusic) but audiologically normal adults, who exhibit deficits in pitch processing but intact temporal processing (Hyde & Peretz, 2004; Murayama, Kashiwagi, Kashiwagi, & Mimura, 2004).

In general, deaf and hearing children produced credible renditions of the target rhythms, but their timing was less accurate and more variable than typical performances of older children or adults. The absence of timing differences between the deaf and hearing children is particularly interesting in view of the fact that most of the hearing children but only a few deaf children were receiving formal music training.

The pitch patterning of deaf children's sung performances was largely unrelated to the pitch patterning of the original songs. Their performances featured a very compressed pitch range, less than one third of the pitch range of hearing children. Casual interactions with the deaf children revealed that all but one child used a considerably greater pitch range in their speech than in their singing, which implies that the problem is not attributable to limitations in vocal production. In general, the magnitude of pitch change that signals important syntactic or pragmatic contrasts in speech greatly exceeds that of typical pitch steps in music (Patel, Peretz, Tramo, & Labreque, 1998; Zatorre, Belin, & Penhune, 2002). Thus, the coarse spectral resolution of current implants may be sufficient for detecting gross differences in speech prosody such as the distinction between statements (i.e., falling terminal pitch) and yes/no questions (i.e., rising terminal pitch) in English, but not for tracking the pitch contours and pitch intervals of music. Estimates of the minimum pitch distance required for correct identification of pitch direction by adult cochlear implant users are in the range of 4 to 12 semitones, with most estimates at the high end of that range (Fujita & Ito, 1999; Vandali et al., 2005).

The contour changes in the present set of songs are likely to be inaccessible to adult implant users, as they were for child implant users. For example, upward and downward pitch changes in deaf children's sung performances were unrelated to upward and downward pitch movement in the target songs, even when the target pitch changes exceeded three semitones. Unlike their hearing peers, child implant users do not seem to distinguish upward from downward pitch motion, which undoubtedly underlies their failure to recognize music from melodic patterns alone (Nakata et al., 2005; Stordahl, 2002; Vongpaisal et al., 2006). Nevertheless, child implant users provided suggestive evidence of pitch differentiation. For example, pitch excursions in their songs were significantly greater when the target pitches (i.e., adjacent notes of the original song) differed than when they did not (i.e., repeated notes). In other words, child implant users detected pitch changes to some extent, but they were unable to discern the direction of such changes, as reflected in their directional errors in singing. Perhaps music training would improve the pitch production skills of child implant users, but it is extremely unlikely that their perception or production deficits would disappear.

If hearing adults participated in a comparable task of singing familiar songs from memory, it is likely that they would maintain consistent timing by humming or using filler syllables such as *la* for unknown words. This strategy was atypical for children, who tended to omit notes corresponding to unknown words. An adultlike strategy involving filler syllables may have processing costs for children. For example, when young hearing children are requested to sing songs using the repeated syllable *la*, the resulting renditions have more pitch and timing errors than do their renditions with conventional lyrics (Adachi & Trehub, 1998).

The small sample in the present study precludes identification of factors that may impede performance such as age at implantation (Mitani et al., in press), length of implant use, and experience hearing or singing the songs. Repeated testing of child implant users could reveal the extent to which greater implant experience and increased familiarity with the songs enhance performance.

Research by Vongpaisal et al. (2006) sheds light on the pitch discrimination skills of child implant users. They presented hearing and deaf children with a series of five tones, the fourth of which was displaced upward or downward in pitch or was unchanged. Children were required to judge the presence or absence of a change. In this very simple listening context, hearing children detected changes as small as 0.25 semitones, and deaf children detected changes as small as 0.5 semitones. For pitch changes presented in a melodic context, however, there were dramatic differences between hearing and deaf children. Whereas hearing children readily detected the change from a major triad to an augmented triad or to a minor triad (i.e., a one-semitone change), child implant users were unable to do so. The present findings and those of Vongpaisal et al. (2006) are consistent with the possibility that deaf children hear small pitch changes as differences in timbre or tone quality, not as different pitch sensations. Perhaps larger pitch differences would provide implanted children with cues to pitch direction, but the magnitude of the requisite pitch differences remains to be determined.

In sum, the present findings indicate that congenitally deaf children who use cochlear implants are capable of singing familiar songs from memory. Moreover, the temporal patterning of their sung renditions is much like that of hearing children. In contrast to hearing children's pitch patterning, which is relatively accurate, child implant users' pitch patterning is grossly distorted. For congenitally deaf children with cochlear implants, the power and pleasure of music probably stem from its rhythm. From a Western perspective, this may seem unusual, but in many parts of the world, rhythm is central to musical expression (e.g., Indian classical music, African drumming). In fact, rhythm plays a critical role in music perception from the early months of life (Hannon & Trehub, 2005; Phillips-Silver & Trainor, 2005). As the present study indicates, timing is also central to the music experience of congenitally deaf implant users for whom melody is largely imperceptible.

Author Note

Portions of this research were funded by the Social Sciences and Humanities Research Council of Canada. We thank the staff of the Nagasaki Bell Hearing Center for their cooperation. We also thank Ryoko Maeda for her assistance in recruiting and testing the hearing children.

Address correspondence to: Sandra Trehub, Department of Psychology, University of Toronto at Mississauga, Mississauga, Ontario L5L 1C6, Canada. E-MAIL *sandra.trehub@utoronto.ca*

References

Adachi, M., & Trehub, S. E. (1998). Children's expression of emotion in song. *Psychology of Music, 26*, 133–153.

Benzon, W. L. (2001). *Beethoven's anvil: Music in mind and culture.* New York: Basic Books.

Bigand, E., Filipic, S., & Lalitte, P. (2005). The time course of emotional responses to music. *Annals of the New York Academy of Sciences, 1060*, 429–437.

Boersma, P., & Weenink, D. (2005). *Praat* (Version 4.3.18). Amsterdam: University of Amsterdam.

Cleary, M., Pisoni, D. B., & Kirk, K. I. (2005). Influence of voice similarity on talker discrimination in children with normal hearing and children with cochlear implants. *Journal of Speech, Language, and Hearing Research, 48*, 204–223.

Dowling, W. J. (1999). Development of music perception and cognition. In D. Deutsch (Ed.), *The psychology of music* (2nd ed., pp. 603–625). San Diego: Academic Press.

Fujita, S., & Ito, J. (1999). Ability of Nucleus cochlear implantees to recognize music. *Annals of Otology Rhinology, and Laryngology, 108*, 634–640.

Gfeller, K., Christ, A., Knutson, J., Witt, S., Murray, K., & Tyler, R. (2000). The musical backgrounds, listening habits and aesthetic enjoyment of adult cochlear implant recipients. *Journal of the American Academy of Audiology, 11*, 390–406.

Gfeller, K., Olszewski, C., Rychener, M., Sena, K., Knutson, J. F., Witt, S., & Macpherson, B. (2005). Recognition of "real-world" musical excerpts by cochlear implant recipients and normal-hearing adults. *Ear & Hearing, 26*, 237–250.

Gfeller, K., Witt, S. A., Spencer, L. J., Stordahl, J., & Tomblin, B. (1998). Musical involvement and enjoyment of children who use cochlear implants. *Volta Review, 100*, 213–233.

Gfeller, K., Woodworth, G., Robin, D. A., Witt, S., & Knutson, J. F. (1997). Perception of rhythmic and sequential pitch patterns by normally hearing adults and adult cochlear implant users. *Ear & Hearing, 19*, 252–260.

Hannon, E. E., & Trehub, S. E. (2005). Metrical categories in infancy and adulthood. *Psychological Science, 16*, 48–55.

Heyman, G. D., & Legare, C. H. (2005). Children's evaluation of sources of information about traits. *Developmental Psychology, 41*, 636–647.

Hyde, K. L., & Peretz, I. (2004). Brains that are out of tune but in time. *Psychological Science, 15*, 356–360.

Kong, Y.-Y., Cruz, R., Jones, J. A., & Zeng, F.-G. (2004). Music perception with temporal cues in acoustic and electric hearing. *Ear & Hearing, 25*, 173–185.

Leal, M. C., Shin, Y. J., Labor, M.-L., Calmels, M.-N., Verges, S., Lugardon, S., Andrieu, S., Deguine, O., & Fraysse, B. (2003). Music perception in adult cochlear implant recipients. *Acta Oto-Laryngologica, 123*, 826–835.

Levitin, D. J. (1994). Absolute memory for musical pitch: Evidence from the production of learned melodies. *Perception & Psychophysics, 56*, 414–423.

Levitin, D. J., & Cook, P. R. (1996). Memory for musical tempo: Additional evidence that auditory memory is absolute. *Perception & Psychophysics, 58*, 927–935.

Loizou, P. C. (1999, September). Introduction to cochlear implants. *IEEE Engineering in Medicine and Biology Magazine*, *18*, 32–42.

McDermott, H., & McKay, C. M. (1997). Musical pitch perception with electrical stimulation of the cochlea. *Journal of the Acoustical Society of America, 101*, 1622–1631.

Mitani, C., Nakata, T., Trehub, S. E., Kanda, Y., Kumagami, H., Takasaki, K., Miyamoto, I., & Takahashi, H. (in press). Music recognition, music listening, and word recognition by deaf children with cochlear implants. *Ear & Hearing.*

Murayama, J., Kashiwagi, T., Kashiwagi, A., & Mimura, M. (2004). Impaired pitch production and preserved rhythm production in a right brain-damaged patient with amusia. *Brain and Cognition, 56*, 36–42.

Nakata, T., Trehub, S. E., Mitani, C., Kanda, Y., Shibasaki, A., & Schellenberg, E. G. (2005). Music recognition by Japanese children with cochlear implants. *Journal of Physiological Anthropology and Applied Human Science, 24*, 29–32.

Patel, A. D., Peretz, I., Tramo, M., & Labreque, R. (1998). Processing prosodic and musical patterns: A neuropsychological investigation. *Brain and Language, 61,* 123–144.

Phillips-Silver, J., & Trainor, L. J. (2005). Feeling the beat: Movement influences infant rhythm perception. *Science, 308*, 1430.

Qin, M. K., & Oxenham, A. J. (2003). Effects of simulated cochlear-implant processing on speech reception in fluctuating maskers. *Journal of the Acoustical Society of America, 114*, 446–454.

Schellenberg, E. G., Iverson, P., & McKinnon, M. C. (1999). Name that tune: Identifying popular recordings from brief excerpts. *Psychonomic Bulletin & Review, 6,* 641–646.

Schellenberg, E. G., & Trehub, S. E. (2003). Good pitch memory is widespread. *Psychological Science, 14,* 262–266.

Shannon, R. V., Zeng, F.-G., Kamath, V., Wygonski, J., & Ekelid, M. (1995). Speech recognition with primarily temporal cues. *Science, 270*, 303–304.

Stordahl, J. (2002). Song recognition and appraisal: A comparison of children who use cochlear implants and normally hearing children. *Journal of Music Therapy, 39*, 2–19.

Svirsky, M. A., Robbins, A. M., Kirk, K. I., Pisoni, D. B., & Miyamoto, R. T. (2000). Language development in profoundly deaf children with cochlear implants. *Psychological Science, 11*, 153–158.

Vandali, A. E., Sucher, C., Tsang, D. J., McKay, C. M., Chew, J. W. D., & McDermott, H. J. (2005). Pitch ranking ability of cochlear implant recipients: A comparison of sound-processing strategies. *Journal of the Acoustical Society of America, 117*, 3126–3138.

Volkova, A., Trehub, S. E., & Schellenberg, E. G. (2006). Infants' memory for musical performances. *Developmental Science 9*, 584–59.

Vongpaisal, T., Trehub, S. E., & Schellenberg, E. G. (2006). Song recognition by children and adolescents with cochlear implants. *Journal of Speech, Language, and Hearing Research 49*, 1091–11.

Wilson, B. S., Schatzer, R., Lopez-Poveda, E. A., Sun, X., Lawson, D. T., & Wolford, R. D. (2005). Two new directions in speech processor design for cochlear implants. *Ear & Hearing, 26,* 73S–81S.

Zatorre, R. J., Belin, P., & Penhune, V. B. (2002). Structure and function of auditory cortex: Music and speech. *Trends in Cognitive Sciences, 6,* 37–46.